Pion Interferometry of $\sqrt{s_{NN}} = 130$ GeV Au+Au Collisions at RHIC

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We present a pion interferometry analysis of first Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV measured by the STAR (Solenoidal Tracker at RHIC) detector. Multidimensional identical-pion correlation functions at midrapidity indicate that the source size grows with event multiplicity. The dependence of the correlations on transverse momentum, reflecting collective transverse flow, is qualitatively similar to that observed at lower energies. Anomalously large sizes or emission durations, which have been suggested as signals of quark-gluon plasma formation and rehadronization, are not observed in the present study. The present results extend the weak $\sqrt{s}$-dependence of the HBT parameters established for central heavy ion collisions at lower energies.

Two-particle intensity interferometry techniques (HBT) have been used extensively to probe the space-time structure of heavy ion collisions [1]. At midrapidity ($y = 0$) and low transverse momentum (p_T), two-pion correlation functions reflect the space-time geometry of the emitting source, while dynamical information (e.g. collective flow) is contained in the momentum dependence of the apparent source size [2–4].

In this Letter we study two-pion correlation functions in the first Au+Au collisions at nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 130$ GeV produced by the RHIC facility at Brookhaven National Laboratory. We also compare our results to similar studies which have been performed at lower energy. Such systematic comparisons may reveal the onset of new phenomena, as the collision energy crosses an onset threshold. We are particularly interested in possible indications that a quark gluon plasma (QGP) has been formed in the collision. Recent observations of strong elliptic flow at RHIC [5] appear to support a hydrodynamic description of the collisions; some [6,7] (but not all [8]) hydrodynamic models predict a significant increase in the pion emission timescale, if a QGP is formed. Several authors [1,4,6,7,9,10] have proposed HBT studies to probe for this long emission duration.

Experimentally, the two-particle correlation function is obtained from the ratio $C_2(\mathbf{q}) = A(\mathbf{q})/B(\mathbf{q})$ (normalized to unity at large $\mathbf{q}$), where $A(\mathbf{q})$ is the measured two-pion distribution of pair momentum difference $\mathbf{q} = \mathbf{p_2} - \mathbf{p_1}$, and $B(\mathbf{q})$ is the mixed background distribution [11], calculated in the same way using pairs of particles taken from different events. Multidimensional correlation functions provide information on the temporal and spatial extent of the pion source [4].

The STAR time projection chamber (TPC) [12,13] was used to record charged particle tracks as they crossed up to 45 padrows of the detector. For P-10 gas in the 0.25 T solenoidal magnetic field, transverse and longitudinal diffusion were both about $350\mu\text{m}/\sqrt{\text{cm}}$. The TPC was read out with 138,000 waveform digitizer channels [14]; the signal shaping width was comparable to the diffusion. For a typical 1.5-meter drift, two-track resolution was limited by the resulting 6 mm signal spread, in addition to geometric spreading due to tracks traversing the padrows at finite crossing angles. This analysis used tracks with $0.125 < p_T < 0.45$ GeV/c and $|y| < 0.5$, for which the reconstruction and π identification efficiencies are high. We present results for three p_T ranges: $0.125 - 0.225$ GeV/c, $0.225 - 0.325$ GeV/c, and $0.325 - 0.45$ GeV/c.

The position of each collision is determined as a part of the event tracking procedure. For the present analysis, we select events with a vertex that is within 75 cm of the mid-plane of the 4-m long TPC. An important feature of two-particle correlation functions is that single-particle phase space and acceptance effects in the q distributions cancel to first order. To preserve this feature in the collider environment (in which the collision vertex– and hence the single-particle acceptance– varies event-to-event), we only mix events which have a primary vertex longitudinal location within 15 cm of each other; however, mixing events over the full ± 75 cm range introduces no significant distortion in the correlation fit parameters, in the present analysis.

Starting with a minimum-bias trigger [5], we characterize the centrality of collisions off-line according to the measured multiplicity of negatively-charged particles with pseudorapidity $|\eta| < 0.5$. After accounting for event reconstruction inefficiency for low-multiplicity events, we estimate that the minimum-bias distribution contains $\sim$90% of the hadronic Au+Au cross section [5]. We analyze $\sim 10^5$ events in each of three bins; bin 3 contains the 12% most central of the measured collisions, bin 2 the next 20%, and bin 1 the next 40%.

Particle identification was achieved by correlating the magnetic rigidity of a track with its specific ionization (dE/dx) in the gas of the TPC. In the momentum region of interest, π, K, and $p/\overline{p}$ are well-separated; contamination of the pion sample by electrons is the primary concern. Based on simulations and on extrapolation from regions of clear e^-/π^- separation, we estimate that electrons comprise about 10% (4%) of the selected tracks in our lowest (highest) p_T bin. Tracks used in the correlations are required to project back to the primary interaction vertex within 3 cm, thereby selecting primarily pions emitted directly from the collision. Contamination from non-pions and pions originating from weak decays (e.g. Λs) reduces the strength of the correlation, characterized by the parameter λ, while leaving the extracted source radii unchanged [15,16].

Although track-splitting (incorrect reconstruction of a single particle as two particles) in the STAR TPC is a small effect in general ($\lesssim 1\%$), it may have a strong impact on two-particle correlation studies at low momentum difference. False pairs generated by track-splitting are removed by a topological cut which requires valid and distinct signals of both tracks on several TPC padrows. For the present analysis, residual effects of track-splitting are negligible.

To eliminate the effect of track-merging (in which two tracks with similar momenta are reconstructed as a single track), we require the tracks in a pair to be well separated (> 2.5 cm at the radius of the TPC inner field cage, 50 cm). In applying this cut also to the mixed-pair background, the effect of event-to-event variation in primary vertex position is taken into account. The anti-merging cut removes significant detector effects, but also discriminates against low-$|q|$ pairs, which carry the correlation signal. This leads to an artificial reduction in the HBT parameters, which we estimate, based on simulations [17], to be 3-6% for the radii and 6-14% for λ, depending on p_T. We correct for this effect in the results presented.

We apply to each background pair a Coulomb correction, calculated via a 5-dimensional Monte-Carlo integration of Coulomb wave functions [4,21] over a spherical Gaussian source of 5 fm radius; this correction is identical to that used by several other groups [15,22,23]. In principle, this procedure over-corrects the correlation function for realistic sources (e.g. in which some pions originate far from the core source). We find that the HBT radii change smoothly by $\sim 10\%$ as the strength of the Coulomb correction is varied from the standard correction to no correction. Here, we restrict ourselves to the standard Coulomb correction used by most previous analyses, allowing for a uniform extension of existing interferometry systematics from lower energy.

One-dimensional correlation functions constructed in the invariant quantity $Q_{inv} = \sqrt{(\mathbf{p}_1 - \mathbf{p}_2)^2 - (E_1 - E_2)^2}$ are fit to the functional form

$$C(Q_{inv}) = 1 + \lambda \exp(-Q_{inv}^2 R_{inv}^2). \quad (1)$$

The 1-D correlation function (and fit) corresponding to our highest multiplicity class and $0.125 < p_T < 0.225$ GeV/c, is shown in Fig. 1a for π^- pairs. The 1-dimensional fit fails in lowest Q_{inv} bins, as has been observed in previous measurements [24]. Hence, the extracted radius $R_{inv} \approx 6.3$ fm is only a rough indication of the space-time extent of the source.

A more detailed characterization of the emitting source is obtained through multidimensional correlation functions. We decompose the momentum difference $\mathbf{q}$ according to the Pratt-Bertsch [4,9] "out-side-long" (indicated by o, s, and l subscripts) parameterization. Here, q_l is parallel to the beam, q_s is perpendicular to the beam and to the total momentum of the pair, and q_o is perpendicular to q_l and q_s. Data are analyzed in the longitudinally co-moving system (LCMS) frame, in which the longitudinal component of the pair momentum vanishes. Figs. 1b-d show one-dimensional projections of the correlation function $C(q_o, q_s, q_l)$ onto the q_o, q_s, and q_l axes, for π^- from the most central collisions.

The 3-dimensional correlation functions are fit with the standard Gaussian form

$$C(q_o, q_s, q_l) = 1 + \lambda \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2), \quad (2)$$

where R_i is the homogeneity length in the i direction [1]. Projections of the fit to the central collisions, weighted according to the mixed-pair background, are shown as curves in Fig. 1.

Systematic errors on the HBT fit parameters have two sources of roughly equal magnitude: (1) the uncertainty on the correction for the anti-merging cut, estimated equal to the correction itself, and (2) the uncertainty associated with the Coulomb correction, $\sim$0.1-0.2 fm in the radii, determined by varying the Coulomb radius by ± 1 fm.

The effect of the single-particle momentum resolution ($\delta p/p \sim 2\%$ in the TPC for the particles under study) is known to induce systematic underestimates of HBT parameters. Using an iterative procedure similar to that used at lower energies [15,24], we have corrected our correlation functions for finite resolution effects. The correction had no effect on the HBT parameters for our lowest p_T cut; for the highest p_T cut, it resulted in a 5% increase in λ and a 8% increase in R_o, while R_s and R_l were unaffected.

The multiplicity dependence of the source parameters is presented in the left panels of Fig. 2, for low-p_T, midrapidity $\pi^-\pi^-$ and $\pi^+\pi^+$ correlations. The parameters for positive and negative pions are similar; the λ parameter is constant, and all three radii increase monotonically with multiplicity. The increase of the transverse radii R_o and R_s with multiplicity is interpreted as a geometrical effect, and is also observed in lower energy measurements [15,25,26]. The increase in R_l with multiplicity, however, is not observed at lower energy [15,26].

The right panels of Fig. 2 show, for the events in multiplicity bin 3, the dependence of the HBT parameters on $m_T = \sqrt{p_T^2 + m^2}$. λ increases with m_T, consistent with studies at lower energy [15,24], in which the increase was attributed to decreased contributions of pions from long-lived resonances at higher p_T.

The radius parameters decrease significantly with m_T. This m_T-dependence, weak at $\sqrt{s_{NN}} \sim 2$ GeV [15] and growing stronger with collision energy [24–26], reflects pion emission from a radially expanding source [1]. The m_T-dependence at RHIC is similar, but not identical, to that observed in central Pb+Pb collisions at the CERN SPS [24,26]. We note in particular the much stronger dependence of $R_o(m_T)$, as compared with lower energy [24,26]. For our highest m_T data, $R_o < R_s$, possibly indicating significant source opacity resulting from the high particle densities generated in RHIC collisions [27,28].

These results represent a significant extension of existing interferometry systematics, allowing a study of the evolution of the emitting source as a function of system energy. Fig. 3 shows the world's dataset of correlation parameters for midrapidity, low-p_T (~ 170 MeV/c) π^- from central Au+Au or Pb+Pb collisions. The parameter λ falls smoothly and rapidly from unity (the expected value from naïve assumptions) at $\sqrt{s_{NN}} \sim 2$ GeV, to about 0.5 at RHIC; this decrease is reproduced by model simulations [15] and is attributed partially to an increased fraction of π^- arising from weak decays as $\sqrt{s_{NN}}$ increases [29]. Since λ is also affected by several experiment-specific effects (e.g. e^- rejection efficiency), we do not focus on the details of its excitation function.

The radius parameter R_s correlates most directly with source geometry [1]. After an initial decrease at AGS energies, attributed to increasing space-momentum correlations [15], R_s appears to rise slightly with collision energy, reflecting a larger freeze-out volume with increasing pion multiplicity. Similarly, R_l does not exhibit a large increase with collision energy, after the initial increase between AGS and SPS energies.

The parameter R_o encodes both geometry and timescale information; in the absence of flow and opacity effects, the emission timescale (duration of freeze-out) is given by $\tau = \sqrt{R_o^2 - R_s^2}/\beta_T$, where β_T is the average transverse velocity of a pion pair. Both R_o and $\sqrt{R_o^2 - R_s^2}$ are relatively independent of energy; we see no evidence for a large increase in emission timescale (e.g. due to QGP formation [6]).

In hydrodynamic models [6,7], the ratio R_o/R_s is a sensitive probe of the Equation of State (EOS). In a purely hadronic (non-QGP) scenario, $R_o/R_s \approx 1.0 - 1.2$, while formation of QGP is predicted to produce $R_o/R_s \approx 1.5 - 10$. This ratio, plotted in the bottom panel of Fig. 3 for low-p_T pions, does not show a significant rise at RHIC. Furthermore, at RHIC R_o/R_s is observed to decrease (from 1.07 to 0.89) with p_T, in contrast to recent transport calculations [30] which include effects of hadronic rescattering after a hydrodynamic stage with a QGP phase. We note, however, that the long emission duration QGP signature is expected [7] to vanish again at energies higher than its onset, due to rapid expansion of the system. Because of the large energy difference between SPS and RHIC, without intervening measurements, we cannot rule out an increase in the emission timescale at some lower, intermediate energy.

In conclusion, STAR has measured two-pion correlation functions in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. Transverse HBT radii grow with event multiplicity, reflecting the evolution of source geometry with centrality. In contrast to studies at lower energies, R_l also increases steadily with multiplicity; more study is required to understand the origin of this effect. The m_T-dependence of the HBT radii is stronger than at lower energies, suggesting emission from a more rapidly expanding source at RHIC, and in particular the much stronger decrease in R_o at high m_T may indicate the onset of opaqueness in the dense system. The pion interferometry excitation function for the heaviest ions now spans nearly two decades in $\sqrt{s_{NN}}$. No sudden jumps in HBT radii are observed, but lower energy RHIC measurements are needed to complete the search for a predicted increase in emission timescale related to the possible onset of QGP formation.

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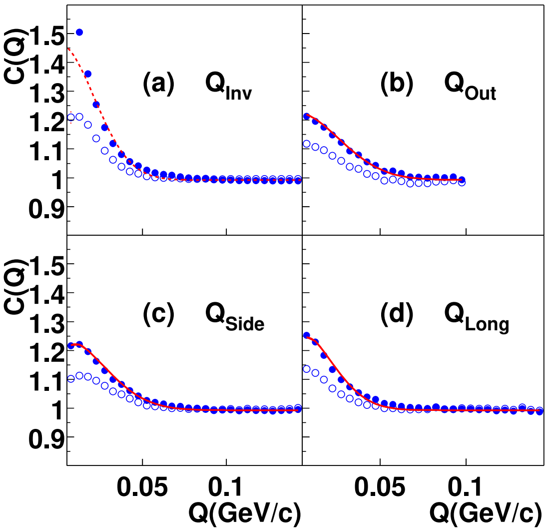

FIG. 1. Coulomb-corrected (full dots) and uncorrected (circles) correlation functions for $0.125 < p_T < 0.225$ GeV/c π^- emitted at midrapidity from central collisions. Shown in panel (a) is the 1-dimensional Q_{inv} correlation function, and in panels (b-d) projections of the 3-dimensional correlation function onto the q_o, q_s, and q_l axes. q-bins are 5 MeV/c wide. To project onto one q-component, the others are integrated over the range 0-0.035 GeV/c. Fits to Coulomb-corrected correlations are shown by curves.

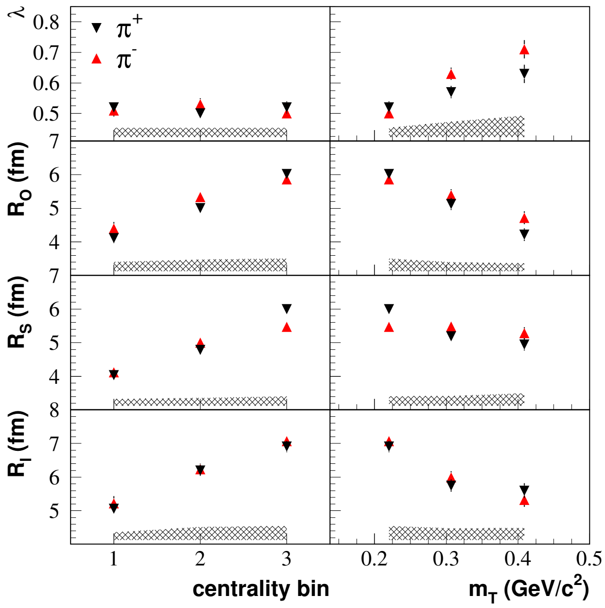

FIG. 2. The multiplicity dependence of the Pratt-Bertsch HBT parameters is shown for ($0.125 < p_T < 0.225$ GeV/c) on the left; bin 3 contains the high-multiplicity events. For central collisions, the m_T-dependences are shown on the right. Error bars indicate statistical uncertainties; systematic uncertainties are represented by the height of the shaded regions below.

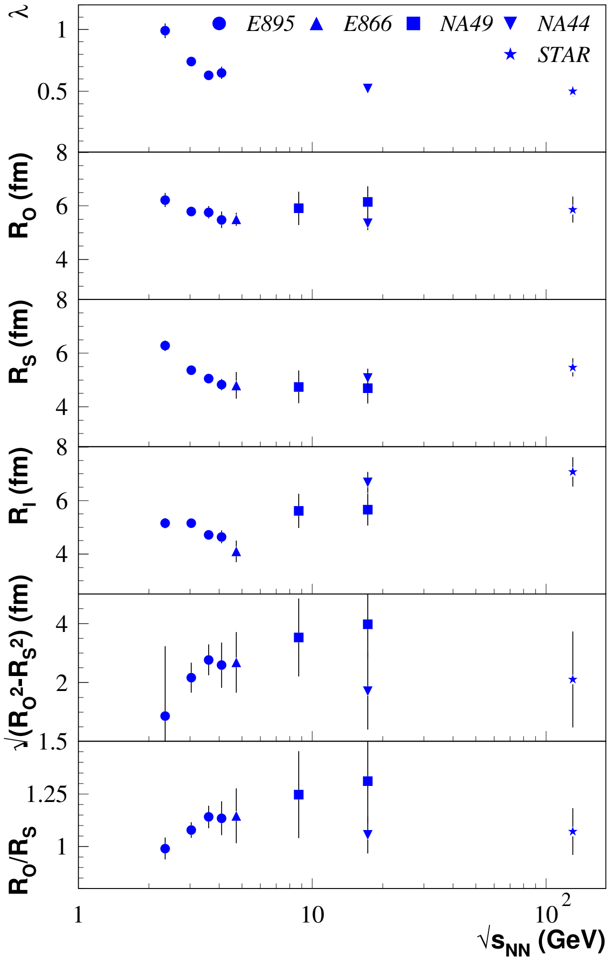

FIG. 3. The energy dependence of π^- HBT radii extracted at midrapidity from central Au+Au or Pb+Pb collisions at $p_T \approx 0.17$ GeV/c. Lower energy points are from AGS and SPS measurements [15,24,25,26]. Error bars on NA44, NA49, and STAR results include systematic uncertainties; error bars on other results are statistical.

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[17] We note that in order to faithfully reproduce the effect of the anti-merging cut on the parameters from a Gaussian fit to the experimental correlation function, we needed to assume a slightly *non*-Gaussian source distribution in our simulations; assuming a purely Gaussian distribution leads to a much weaker effect than is observed. In realistic transport calculations [18,19] such non-Gaussian distributions are generated by dynamic expansion [20] and "halo" emission from long-lived resonances.
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